UCRL- 84311
PREPRINT

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This paper was prepared for publication in the
proceedings of the 17th JANNAF Combustion Meeting,
NASA/Langley Research Center
Virginia, September 22-26, 1980

August 15, 1980

Lawrence Livermore Laboratory

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ABSTRACT

This paper describes current progress in the calculation of nonsteady boundary layers connected with internal flows for the purpose of discovering the principal wall erosion mechanisms. A time-dependent system of equations describing the laminar and turbulent viscous layer is solved numerically by means of an alternating-direction-implicit (ADI) scheme for prescribed transient and streamwise-varying core flow conditions. Validity of the method is demonstrated by comparison of present results with those obtained by previous analyses. Earlier calculations of compressible turbulent flow cases showed that high heat fluxes at the wall due to turbulence and changing core conditions could bring about severe temperature rise at the wall. Present results indeed display a marked rise in wall temperature which may cause melting and ablation, and hence erosion of the surface.

INTRODUCTION AND FORMULATION

The purpose of this work is to determine the fundamental mechanisms of erosion in gun barrels and other systems involving hot propellant flows. In order to investigate the interaction between the interior surface and the hot flowing gas, assuming conditions of unsteady core flow and wall heat transfer as well as turbulence and reactions between chemical species, a time dependent description of the fluid boundary layer adjacent to the surface is formulated. This consists of a set of time variant conservation equations which are to be solved simultaneously. Due to the complex nature of hot gas erosion and of the various coupled equations a step-by-step approach to the problem is taken. Initially only the equations of mass, momentum, and thermal energy for unsteady boundary layers are treated. Results obtained by numerical solution of this smaller system of equations are presented and discussed. For propellant gas flows thermodynamic equilibrium and eddy diffusivity expressions of Cebeci and Smith[1] are presently used in the scheme. A new "responding wall temperature" equation is also included in the setup in preparation for subsequently studying melting and ablation of the surface itself.

The conservation equations are:

Continuity:

$$\frac{\partial}{\partial t}(\rho r^j) + \frac{\partial}{\partial x}(\rho u r^j) + \frac{\partial}{\partial y}(\rho v r^j) = 0$$

*Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract #W-7405-Eng-48.

Momentum:

$$\rho \frac{\partial u}{\partial t} + \rho u \frac{\partial u}{\partial x} + \rho v \frac{\partial u}{\partial y} = - \frac{\partial p}{\partial x} + \frac{1}{r^j} \frac{\partial}{\partial y} [r^j (\mu \frac{\partial u}{\partial y} - \rho \overline{u'v'})]$$

Energy:

$$\rho \frac{\partial H}{\partial t} + \rho u \frac{\partial H}{\partial x} + \rho v \frac{\partial H}{\partial y} = \frac{1}{r^j} \frac{\partial}{\partial y} [r^j\{\frac{\mu}{Pr} \frac{\partial H}{\partial y} - \overline{\rho v'H'} + \mu(1 - \frac{1}{Pr}) u \frac{\partial u}{\partial y} \}]$$

where

$$j = \left\{\begin{matrix} 0 \text{ for two-dimensional flow} \\ 1 \text{ for axisymmetric flow} \end{matrix}\right\}.$$

The prime signifies a fluctuation, and the bar above the prime terms denotes a time-averaged mean value. Other symbols are defined in NOMENCLATURE.

As previously noted the eddy viscosity concept is used here for the Reynolds shear stress term, $-\overline{\rho u'v'}$, and the term $-\overline{\rho v'H'}$ based on Cebeci and Smith.[1] Thus we have:

Inner region:

$$\varepsilon_i = 0.16 \ y^2 \ [1 - \exp \ (-y/A)]^2 \left|\frac{\partial u}{\partial y}\right|$$

Outer region:

$$\varepsilon_0 = 0.0168 \ u_e \ |\delta^*|\gamma$$

where A is a constant for a given streamwise location in the boundary layer, defined as 26 $\nu(\tau_w/\rho_w)^{1/2}$ and γ is the intermittency factor approximated as $[1 + 5.5(y/\delta)^6]^{-1}$.

The spatial coordinates are transformed by application of the Probstein-Elliot[2] and Levy-Lees[3] methods to the original set of nonlinear, coupled partial differential equations. Then the equations are differenced and solved numerically by a variation of the ADI method of Beam and Warming,[4] which is in turn derived from the method of Douglas and Gunn.[5] This scheme is second-order time accurate, spatially factored, and noniterative. Transient and streamwise varying core flow conditions are prescribed at the edge of the viscous layer as boundary conditions. The computer program in which this solution scheme is implemented is called TRAVIS (for TRAnsient-VIScous) and will often be referred to in the body of this paper interchangeably with the scheme itself.

RESULTS AND DISCUSSION

The TRAVIS code was initially tested for its validity on some well-studied physical cases. The first of these was the case of an incompressible unsteady laminar flow over a flat plate. A Blasius velocity profile on the upstream boundary and the Rayleigh-Stokes flow field were prescribed on all downstream stations as initial conditions. As time elapsed all the velocity profiles developed into the Blasius profile. Hall[6] originally obtained a solution to this problem and our results agreed well with his results. The scheme was next applied to compressible laminar flows of perfect gasses with a Prandtl number of unity. The resulting thermal profiles matched the velocity profiles, another proof of correctness of the present scheme. Next, a turbulence model was added to the scheme. Figure 1 shows the timewise development of the turbulent velocity profile far downstream from the leading edge. The change in the profiles near the wall and the increase in boundary layer thickness compared to the laminar cases are evident. These turbulent profiles compared well with those obtained by Blottner.[7] Because the turbulent boundary layer thickness in terms of η may be 100 or greater for Reynolds numbers on the order of 10^9, say, the variable mesh size scheme described by Chong[8] was incorporated into TRAVIS to permit efficient calculation of flow characteristics regardless of layer thickness. The turbulent thermal profiles shown in Fig. 2 demonstrate behavior similar to that of the turbulent velocity profiles over time.

The next step was the inclusion of spatially and temporally varying total energy potential between the wall and the edge, i.e., varying $\Delta H = H_e - H_w$. In the "responding wall" model heat from the core flow is transferred through the boundary layer to the wall causing wall temperature, T_w, to rise. In turn, the viscous layer flow is itself affected by resulting changes in H. Based on the unsteady thermal profile distributions in the direction normal to the flow it is possible to obtain the heat transfer rate at the surface. Figure 3 shows the thermal energy flux, C_H, at different times along the surface in the streamwise direction. Note the sudden increase and then the gradual decrease in heat flux in response to changing core flow conditions.

Finally, Fig. 4 shows the corresponding wall temperatures for these times for a steel surface whose thermal conductivity and thermal diffusivity were held constant. Sizable increases in surface temperature with time are demonstrated, especially in the upstream region.

In summary, it seems apparent from present results that there are considerable timewise variations in flow characteristics. Thus we believe it is desirable for any erosion analysis to take into account all possible effects of timewise fluctuations of such physical parameters as heat flux and mass flux at the wall. In our future research on the erosive phenomena in combustion environments, we plan to consider a more elaborate turbulence model, chemically reacting flows, and melting-surface situations.

NOMENCLATURE

Symbols

H	total enthalpy
p	pressure
Pr	Prandtl number
t	time
u	x-component of velocity
v	y-component of velocity
x	distance along the surface measured from leading edge or from stagnation point
y	distance normal to x
γ	intermittency factor
δ	boundary layer thickness
δ^*	displacement thickness
ε	eddy viscosity
η	transformed y-coordinate $(u_e \int^y \rho r^j dy)/\sqrt{2\xi}$
θ	dimensionless total enthalpy $(H - H_w)/(H_e - H_w)$
μ	viscosity
ν	kinematic viscosity
ξ	transformed x-coordinate $(\int^x \rho_e \mu_e u_e r^{2j} dx)$
ρ	density
τ	shear stress

Subscripts

e	outer edge of boundary layer
w	wall (surface)

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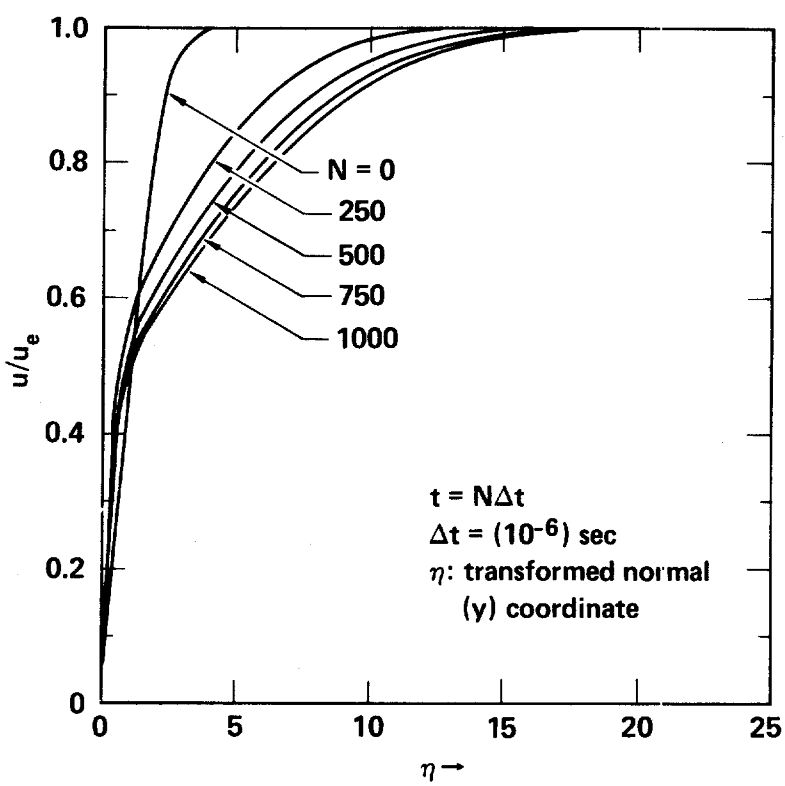

Figure 1. Timewise Development of Turbulent Velocity Profiles

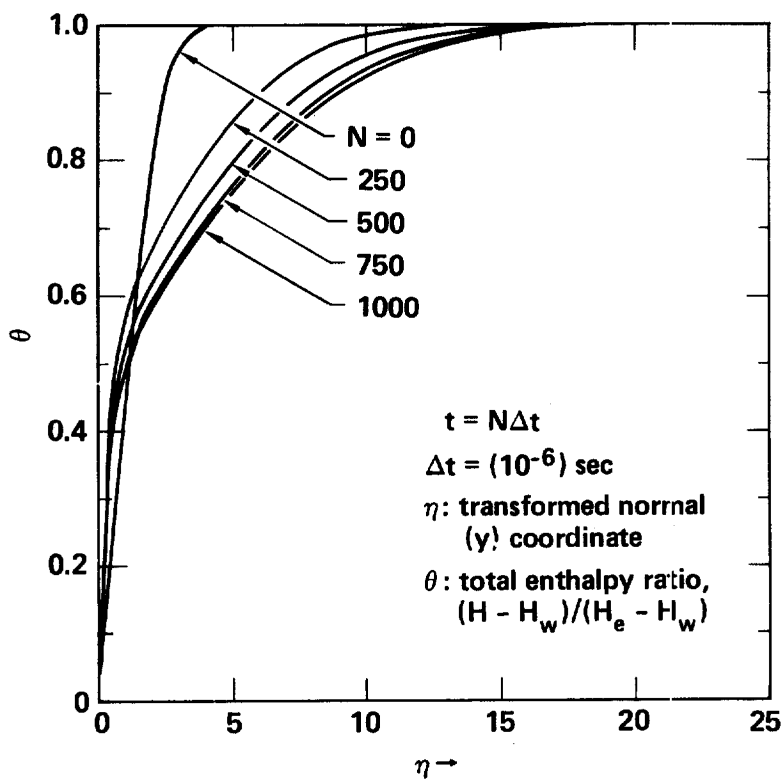

Figure 2. Timewise Development of Turbulent Thermal Energy Profiles

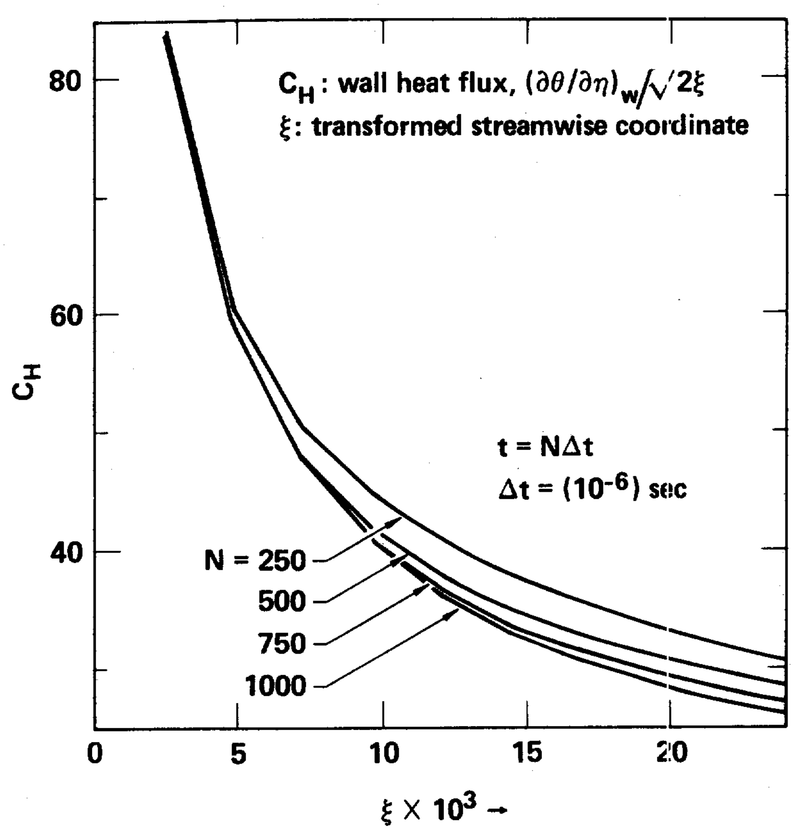

Figure 3. Transient Heat Fluxes at the Wall

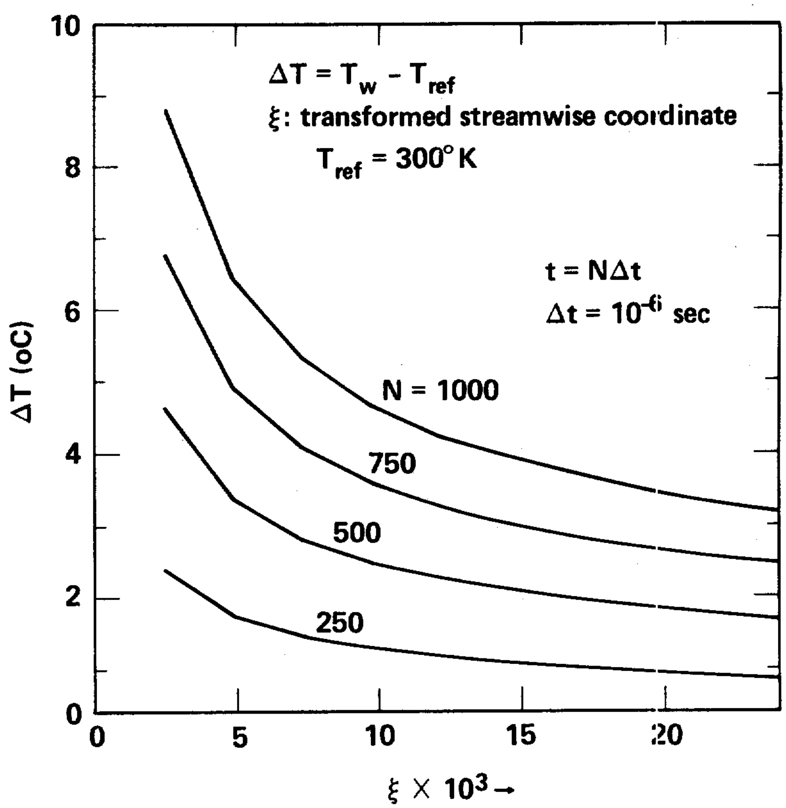

Figure 4. Wall-Temperature History in Response to Energy Flux at Surface